Spatial Variation of Corn Response to Irrigation

E. J. Sadler, C. R. Camp, D. E. Evans, J. A. Millen

Abstract. *Lack of basic knowledge about spatially varying crop response to irrigation hinders optimal irrigation management and economic analysis for site–specific agriculture. The objectives of this research were to measure the mean response of corn to irrigation amounts on 12 soil map units and compare variation in the response within and among soil map units. This experiment was implemented from 1999 through 2001 with a center–pivot irrigation machine that had been modified to enable site–specific irrigation on small plots within a representative, highly variable Coastal Plain field. Four irrigation treatments (0%, 50%, 100%, and 150% of a base rate designed to hold soil water constant) and two N treatments (135 and 225 kg/ha, the recommended rainfed and irrigated rates) were imposed in 2 × 4 factorial randomized complete blocks on eight soil map units, plus randomized incomplete blocks on four additional map units. The water treatments had consistently significant main effects in the analysis of variance (ANOVA) in both linear and quadratic forms at the 1% level, and the variation within soil map units was significant at the 5% level in the latter two years and at the 1% level in 1999. Variation in yield among soil map units at any point on the response curves approximated 25% of the maximum yield in all three years. Variation in mean irrigation amounts to produce maximum yield in the eight most common map units was 61%, 61%, and 120% of the base rate amount in the three years. These data, the first such known for any soil, crop, or location in the world, have significant implications for the design, management, and economic profitability of irrigation on spatially varying soils. While the obvious design and management change would be from whole–field to site–specific approaches, even under whole–field situations, designers should consider more strongly the management zone size, range of application rates, and need for documentation.*

Keywords. *Site–specific agriculture, Deficit irrigation, Irrigation, Irrigation production function, Corn,* Zea mays, *Center–pivot irrigation.*

Water was the first managed input for crop production, with archaeological indications from some 8,000 years ago in the Nile Valley (Hoffman et al., 1990a) and later in other river valleys of Mesopotamia, China, India, and the Americas. Civilizations rose, and sometimes fell, as a result of long–term changes in water supply (Sadler and Turner, 1993). Consequently, there is a long history of research in irrigation, resulting in new methods of application and new management of these methods (cf. Hagan et al., 1967; Jensen, 1980; Hoffman et al., 1990b; Stewart and Nielsen, 1990).

Much of the effort in designing and managing irrigation systems has been centered on irrigation water use efficiency, with the concomitant interest of application uniformity across the managed area (Heermann et al., 1990, in general; Bruce et al., 1985; Camp et al., 1988a, 1988b; Camp and Campbell, 1988, for southeastern U.S.). Achieving the most efficient use of applied water requires knowledge about the response of the crop to varying amounts of applied water, sometimes termed a production function (Hexem and Heady, 1978; Stegman et al., 1980; Vaux and Pruitt, 1983; Howell et al., 1990). Studies of the effects of irrigation non–uniformity on the crop response provide the earliest work on spatial variation in crop response to water, which leads into the topic of variable–rate, or site–specific, irrigation (see review in Adamsen et al., 2000). However, in all these works, the reported values were means across replications in space. Further, crop production functions have historically been determined under conditions of uniform irrigation management, analogous to the research on crop response to fertilizer, which has been studied under similarly uniform fertility management. There is considerable question whether relationships obtained under uniform management can be applied in site–specific agriculture, either for fertility (Hergert et al., 1997) or for water (Sadler et al., 2000b).

As mentioned above, research that studied the effects of irrigation non–uniformity, with the intent to quantify the costs thereof, might potentially be reevaluated to search for insights into the present issue of site–specific crop response functions. Relationships where crop response has been determined using variable rates of irrigation, either by design (Or and Hanks, 1992), as a result of spatial variability in soil properties (Bucks and Hunsaker, 1987), or as an artifact of the surface irrigation method (Bautista and Wallender, 1985) may have some value in guiding future research in managing site–specific irrigation in regions similar to where these studies were conducted, providing the original data remain accessible. In addition, research studying yield as related to spatially varying soil water on dryland (e.g., Logsdon et al., 1999; Timlin et al., 1999) or irrigated crops (e.g., Coelho et al., 1999; Lascano et al., 1999) can contribute to fundamental relationships. These recent works indicate rising interest in site–specific crop responses to water and related soil characteristics, but in all cases, physical limitations of the research facility have prevented the determination of crop response or production functions for site–specific irrigation management. Yet these functions are required for strategic

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decisions about profitability, tactical decisions about irrigation system design, and operational decisions regarding optimization of irrigation management (e.g., Yaron and Bresler, 1983).

One report is available concerning profitability of site–specific water management. Because empirical data needed for the economic analyses were not available, theoretical crop production functions were developed by Watkins et al. (1999). They used a computer simulation model to evaluate the economic and environmental benefits of site–specific irrigation of potatoes in Idaho. This presumes the model correctly represents the crop sensitivity to water, which is a very stringent criterion for a model's success (Sadler and Russell, 1997). Interestingly, Watkins et al. (1999) concluded that variable–rate water application was more likely to be both economically and environmentally beneficial than variable–rate nitrogen application for potatoes under the Idaho conditions.

Empirically obtaining site–specific crop response functions requires irrigation facilities suitable to study these relationships. These are not widely available, having been built only recently in very few locations worldwide. These include a linear–move site–specific irrigation machine for research purposes at Fort Collins, Colorado (Fraisse et al., 1992; Duke et al., 1992), two site–specific center–pivot irrigation systems on production fields in Idaho (King et al., 1995), two site–specific center–pivot irrigation machines for research purposes in Florence, South Carolina (Camp and Sadler, 1994; Sadler et al., 1996; Omary et al., 1997), and a custom control system on a commercially operated center–pivot system in Washington (Evans et al., 1996; Evans and Harting, 2000). This last example was used to adapt commercial systems for site–specific application in Washington as well (Harting, 1999). (Readers interested in these facilities can see Sadler et al., 2000c; Evans et al., 2000; and Buchleiter et al., 2000, for recent reviews of the state of this art.) These facilities, particularly the ones sited on research campuses, have the capability to apply irrigation on a site–specific basis, with spatial resolutions ranging from 10 m to approximately 70 m. Thus, for the first time, it is possible to actually measure crop production functions on a site–specific basis to permit better irrigation and nutrient management decisions.

The site–specific center–pivot irrigation facility at Florence, South Carolina, is located on a representative Coastal Plain field that has been extensively studied (Karlen et al., 1990; Sadler et al., 1995, 1998, 2000a, 2000b, 2002; Camp et al., 2000b). This field includes 12 soil map units (1:1200 scale) common to the southeastern U.S. Coastal Plain. Yield maps have been obtained under uniform culture since 1985. The supporting data, when added to the capabilities of the irrigation facility, make the site uniquely suited to obtain site–specific crop response data. The capabilities of this facility enable the current research, which has the following objectives: (1) to measure the mean response of corn to irrigation amounts on 12 soil map units, and (2) to compare variation in the response within and among soil map units.

Materials and Methods

The experiment was conducted during the 1999–2001 corn growing seasons using the site–specific center–pivot irrigation facility at Florence, South Carolina (34.25° N, 79.80° W). The capabilities of the center pivot both enabled and constrained the experimental design. This section will describe the field site, the experimental design, the agronomic practices, the site–specific center pivot, and the data analyses.

This site had been mapped on a 1:1200 scale by USDA–SCS staff in 1984 (USDA–SCS, 1986). Brief descriptions of the 12 soil map units under the center pivot are given in table 1. Further descriptions of the soil map units and background information on the field site before the pivot was installed can be found in Karlen et al. (1990) and Sadler et al. (1995).

Map unit boundaries pose a challenge to experimental design. Karlen et al. (1990) treated soil map unit as a class variable in the general linear model, but because the soil map unit could not be placed in random locations, for this experiment it was decided to treat soil map unit as a fixed effect. This is similar to the design used by plant breeders, for instance, where a series of small experiments is conducted at multiple locations. This required the use of replication within soil as the error term for the soil main effect. Further, the experiment was to be analyzed using spatial tools, which required that plots be distributed somewhat across the field. Therefore, the number of plots in a particular soil map unit necessarily depended on the area of the map unit. And in some cases, smaller soil map units did not have sufficient area to include complete blocks. Multiple blocks in some soil map

Table 1. Description of soils located in the center pivot experiment (after Sadler et al., 2002).

Symbol	Soil Classification
BnA	Bonneau loamy fine sand (lfs), 0% to 2% slopes (loamy, siliceous, thermic Grossarenic Paleudult)[a]
Cx	Coxville loam (clayey, kaolinitic, thermic Typic Paleaquult)
Dn	Dunbar lfs (clayey, kaolinitic, thermic Aeric Paleaquult)
Do	Dunbar lfs, overwash (clayey, kaolinitic, thermic Aeric Paleaquult)
ErA	Emporia fine sandy loam (fsl), 1% to 2% slopes (fine–loamy, siliceous, thermic Typic Hapludult)
GoA	Goldsboro lfs, 0% to 2% slopes (fine–loamy, siliceous, thermic Aquic Paleudult)
NbA	Noboco lfs, moderately thick surface, 0% to 2% slopes (fine–loamy, siliceous, thermic Typic Paleudult)
NcA	Noboco lfs, thick surface, 0% to 2% slopes (fine–loamy, siliceous, thermic Typic Paleudult)
NfA	Noboco fsl, 1% to 2% slopes (fine–loamy, siliceous, thermic Typic Paleudult)
NkA	Norfolk lfs, moderately thick surface, deep water table, 0% to 2% slopes (fine–loamy, siliceous, thermic Typic Paleudult)[b]
NoA	Norfolk lfs, thick surface, 0% to 2% slopes (fine–loamy, siliceous, thermic Typic Paleudult)[b]
NrA	Norfolk fsl, 1% to 2% slopes (fine–loamy, siliceous, thermic Typic Paleudult)[b]

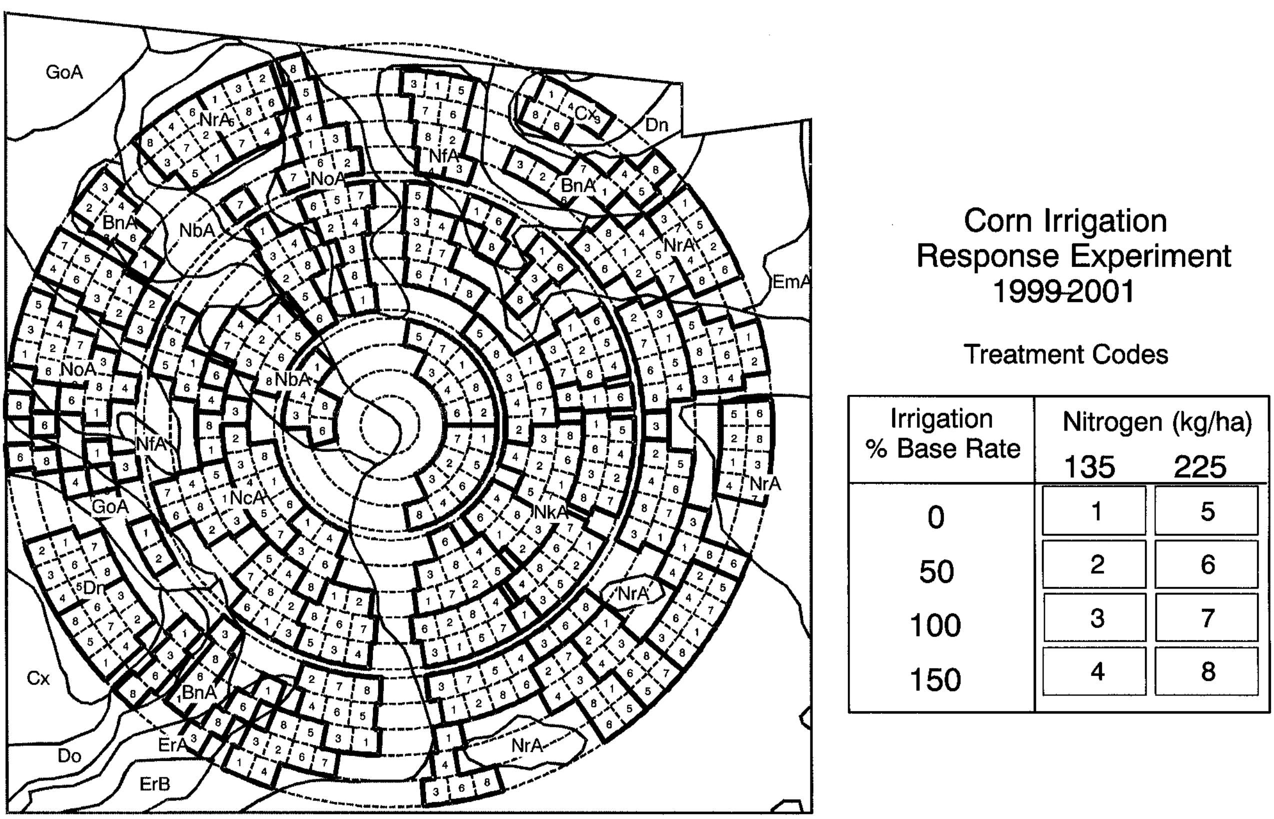
[a] Reclassified in March 1990 to loamy, siliceous, thermic Arenic Paleudult.
[b] Reclassified in March 1988 to fine–loamy, siliceous, thermic Typic Kandiudult.

units and incomplete blocks in others created an imbalanced design. Gotway Crawford et al. (1997) discuss statistical theoretical considerations involved in comparing whole–field management vs. site–specific management, some of which apply to the current experiment. However, this design was a compromise between the need for classical and spatial statistical analyses, and therefore, neither approach could be fully optimized.

Irrigation and N treatments (discussed below) were imposed in 4 × 2 factorial randomized complete blocks (RCBs) where sufficient area existed within the soil map unit boundaries. Where insufficient area was available, randomized incomplete blocks (RICBs) were used. On some larger soil map areas, multiple RCBs were imposed. The number of RCBs was 39, and the number of RICBs was 19, resulting in a total of 396 plots. The plot sizes were nominally 9.1 m × 9.1 m at the outer boundaries and 6.1 m × 6.1 m in the central control areas (see pivot description below regarding sizes). The plot diagram and the soils map are shown in figure 1. Treatments were imposed continually on the same plots, so yield responses reflect the cumulative effects of water or nutrient excesses or deficits.

The schedules of cultural operations for the three years are given in table 2, and common elements are given here. Conventional surface tillage culture was used. This included initial diskings, broadcast dry granular fertilizer applications at rates shown in table 2, and a combined pre–plant herbicide application and incorporation. Corn (Pioneer 3163) was planted around the pivot circle with a 6–row planter that had in–row subsoilers to a depth of 40 cm. Row spacing was 0.76 m, and the final plant populations in the three years ranged from about 64,000 to 66,000 plants/ha, chosen to be intermediate between the regional recommendations for rainfed and irrigated corn. Pre–plant and post–emergence herbicides and a banded insecticide were applied as recommended by South Carolina Cooperative Extension Service at rates shown in table 2.

The four irrigation treatments were 0%, 50%, 100%, and 150% of an irrigation base rate (IBR) determined by soil water potential (SWP) values and meteorological conditions. Soil water potential was measured using tensiometers at two depths (30 and 60 cm) in multiple locations representing several soil map units. In 1999, tensiometers were placed in the 100% IBR treatments in eight sites, two in each of the Cx, NcA, NkA, and NoA map units. In 2000 and 2001, tensiometers were placed in all treatments for six blocks: Cx, BnA, Dn, NcA, NkA, and NoA map units. The first was an incomplete block with five plots, and the others were complete blocks, making 45 tensiometer locations. Measurements were recorded at least three times each week. Irrigation was initiated in all irrigation treatments when mean SWP at the 30–cm depth in the 100% base rate treatments was less than or equal to –30 kPa. The IBR varied during the growing season (4 to 13 mm/application) depending upon crop growth stage and weather conditions but was intended to replace evapotranspiration (ET). Standard meteorological variables were measured at an automated weather station on the experimental site, approximately 100 m west of the western edge of the pivot circle in 2000–2001 and about 300 m southwest in 1999. In 1999, air temperature and dew point data were also obtained for the Florence Regional Airport (http://lwf.ncdc.noaa.gov/oa/ncdc.html).



Irrigation % Base Rate	Nitrogen (kg/ha) 135	225
0	1	5
50	2	6
100	3	7
150	4	8

Figure 1. Diagram of experimental design for corn response experiment, with soil map unit boundaries. The heavy lines show blocks within soil map units.

Table 2. Cultural operations during the three seasons.

Operation	Season		
Material Applied	1999	2000	2001
Disking 1 date	17 Feb.	3 March	9 Feb.
Disking 2 date	20 March	13 March	19 March
Disking 3 date	—	23 March	27 March
Granular fertilizer application date	23 March	24 March	28 March
Fertilizer, N–P–K (kg/ha)	31–23–44	45–43–139	68–43–138
Pre–plant herbicide and incorporation date	29 March	30 March	9 April
Preplant metolachlor (kg/ha)	2.8	0.8	0.9
Preplant atrazine (kg/ha)	—	1.0	1.1
Planting date	3 April	31 March	11 April
Banded terbufos (kg/ha)	1.0	1.0	1.0
Emergence date	9 April	9 April	18 April
Post–emergence herbicide date	11 May	5 May	15 May
Spray over top atrazine (kg/ha)	2.2	1.7	1.7
UAN 24S application date	2–4 June	24–25 May	18–19 May
UAN24S rate (low) (kg/ha)	104	90	67
UAN24S rate (high) (kg/ha)	194	180	157
Tasseling date	14 June	15 June	13 June
Physiological maturity date (by GDU)	7 August	3 August	9 August
Harvest date	31 August – 7 Sept.	13 Sept. – 2 Oct.	5 Sept. – 14 Sept.

GDU = Growing degree units with limits of 10°C and 30°C.

The two N–fertilizer treatments were the recommended rainfed and irrigated rates (135 and 225 kg/ha), corresponding to target yields of 6.3 and 10.1 Mg/ha. These rates were held constant across irrigation amounts, which meant that a low–N irrigated plot and a high–N rainfed plot were included in the design. While these combinations would not be employed in producer's fields, they were included to complete the factorial, because simultaneously increasing both fertility and irrigation amounts would confound the interpretation. Urea ammonium nitrate with sulfur (UAN 24S) was applied according to the treatment plan via the irrigation system during the periods shown in table 2.

Irrigation and N treatments were imposed using a commercial, three–span, center–pivot irrigation system that had been modified to provide site–specific water and fertilizer applications. The center pivot was 137 m long and had an irrigated area of 5.8 ha. The variable–rate water application system consisted of 13 segments along the truss length, each 9.1 m long, ending on the outer tower. Each segment had three manifolds with six nozzles sized to provide application depths of 1×, 2×, and 4×, with specific depths controlled by pivot speed. With the center pivot operating at 50% speed, each segment could independently apply 0 to 12.7 mm in seven 1.8–mm steps. For this experiment, the second, fourth, and sixth flow rates were used. For these, the ranges in the manufacturer's specifications were within 8%, 6%, and 5% of the design numbers of 3.6, 7.2, and 10.8 mm. The industrial spray nozzles (see Omary et al., 1997, for specifications) had wetted radii of approximately 2.5 m, and because they were spaced 1.5 m apart, overlap between segments required a buffer zone of approximately 1.5 m on either side of plot boundaries, resulting in the 6.1 × 6.1–m control area. Uniformity in this control area had previously been predicted from wetting patterns and nozzle spacing by Omary et al. (1997) to range from 87% to 95% and was confirmed for test segments in both radial and tangential directions by Camp et al. (2000a).

The variable–rate application system was controlled by a computer connected to a programmable logic controller (PLC). Using angular position data obtained from the center pivot controller, spatially indexed data stored on the computer, and software developed by USDA–ARS in Florence, the PLC switched the proper valves to obtain the appropriate application depth for each management zone. Nitrogen fertilizer was injected into the center pivot water line with a variable–speed pump at rates proportional to the aggregate flow rate to maintain a constant concentration in the water distribution system. Variable N amounts were applied to each management zone by varying the water amount, and therefore were constrained to similar accuracy of application. Additional details regarding the site–specific center–pivot irrigation systems were reported by Sadler et al. (1997), Omary et al. (1997), and Camp et al. (1998, 2000a).

Each year, a 6.1–m length of two rows near the center of each plot was harvested using a plot combine. The harvested grain was weighed, corrected to 15.5% moisture, and expressed per unit ground area. Yield data were statistically analyzed using analysis of variance (SAS, 1990). For the analyses, the irrigation amount was added to the seasonal rainfall total for a total water value. Where no significant differences occurred between N treatments, the values for low and high N treatments were considered as two observations for the same water treatments and soils.

In addition to the analysis of variance mentioned above, two additional calculations were performed on the data from the RCBs. The general response form, when concave–down quadratic, was fitted using regression analysis to yield the coefficients (A_0, A_1, and A_2) in equation 1, where *Irr* is irrigation applied in mm:

$$Yield = A_0 + A_1 \times Irr + A_2 \times Irr^2 \quad (1)$$

The maximum response to irrigation is defined as the maximum within the imposed treatment range. For concave–down forms ($A_2 < 0$), this will be either the point at which the derivative is zero, or an endpoint. If the former, then the value of irrigation that results in the derivative being zero is shown in equation 2:

$$Irrmx = \frac{-A_1}{2 \times A_2} \tag{2}$$

If a zero derivative did not exist within the range, then the endpoint was chosen.

The quadratic equation was then evaluated at this value for irrigation. The response to irrigation was then found by subtracting the intercept (A_0) from the maximum yield. Means and extreme values for maximum yield, irrigation at that point, and maximum response to irrigation were computed for each soil map unit for which complete RCBs existed. This post–experiment technique is different than simply choosing maximums from experimental data in that it allows intermediate irrigation levels to be selected as the hypothetical maximum.

Daily reference evapotranspiration was computed using the ASCE standard for grass (Walter et al., 2000), and evapotranspiration for both a rainfed and a well–watered corn crop was calculated using the dual–crop–coefficient method of Allen et al. (1998). For this determination, the initial value of Kc was 0.15 and lasted until emergence. From then until tasseling, it increased linearly from 0.15 to 1.15, where it was constant until physiological maturity, defined as growing degree units (GDU) of 1580° C–days computed using the limits of 10° C and 30° C and confirmed with observations of black layer formation in 1999 and 2001. Weather data for these calculations were obtained from the on–site weather station, supplemented in 1999 with air temperature and dew point data from the Florence Regional Airport. Comparisons were also made between the on–site weather data and the Florence Regional Airport data for 2000–2001 to ensure that the use of more–distant data in 1999 caused no bias.

Results and Discussion

The cumulative evapotranspiration, reference evapotranspiration, rain, and irrigation values for all treatments during the 1999, 2000, and 2001 corn growing seasons are given in figures 2, 3, and 4. During all years, the rainfall totals from planting to maturity were from 10% to 30% less than the 30–year climatic normal rainfall for the April through July period of 410 mm (table 3). Conditions were quite similar in 1999 and 2000, both generally being considered drought years, but the rainfall totals were considerably different. There was 29% (83 mm) more rain in 2000 than in 1999, with more than 100 mm of it coming in a 2–week period near 1 June. On the other hand, distribution of rainfall was much more uniform during grain fill in 2001, and most considered 2001 a non–drought year, despite the seasonal total rainfall being 78 mm, or nearly 20%, less than the normal. Part of the difference between 2001 and the prior two years might be explained by relatively fewer high–intensity rainfall events in 2001. A spatial analysis of runoff and surface redistribution will be required to confirm if the higher values for rain + irrigation in 1999 and 2000 would be reduced as a result of a lower effective rainfall.

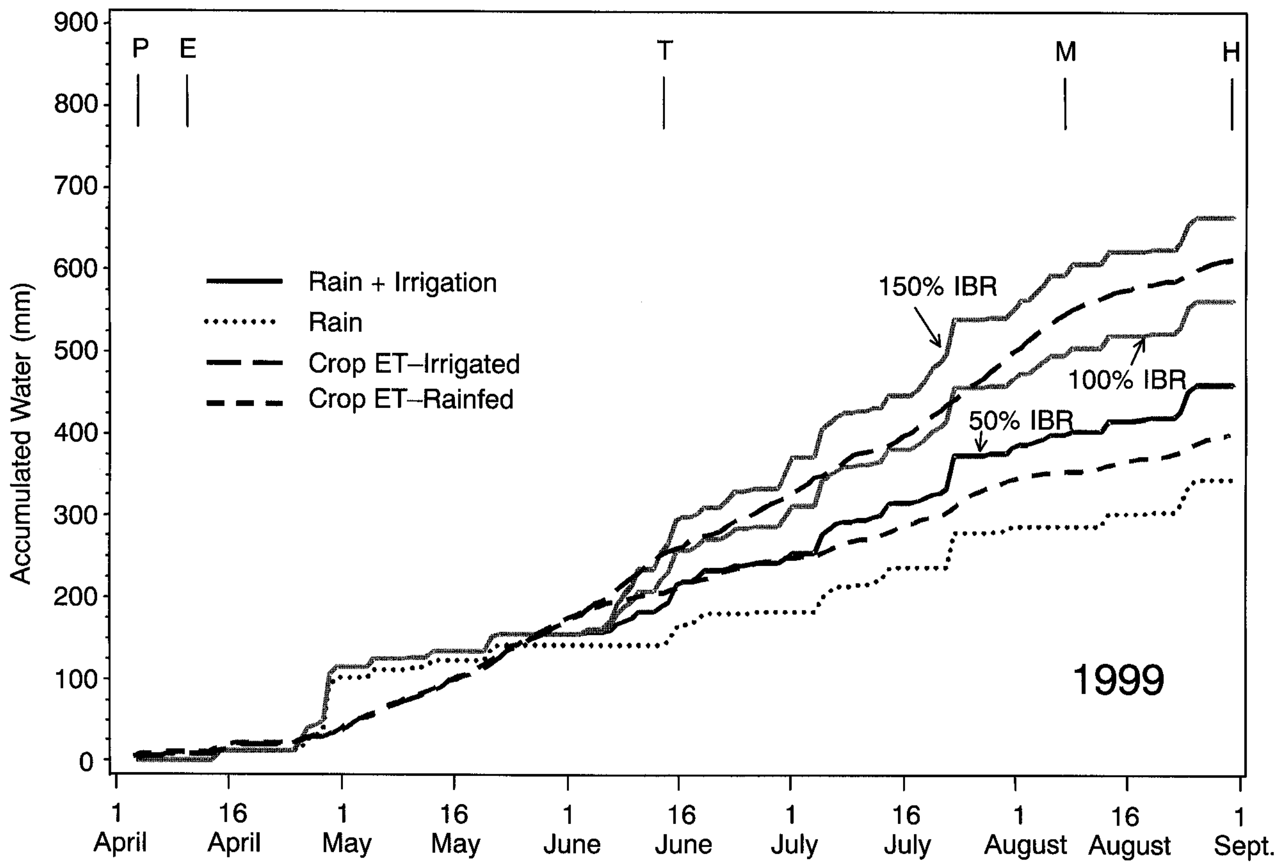


Figure 2. Cumulative rainfall, calculated rainfed and well–watered corn evapotranspiration, and rain plus irrigation for all irrigation treatments during the 1999 corn growing season. P, E, T, M, and H notations across the top indicate planting, emergence, tasseling, maturity, and harvest.

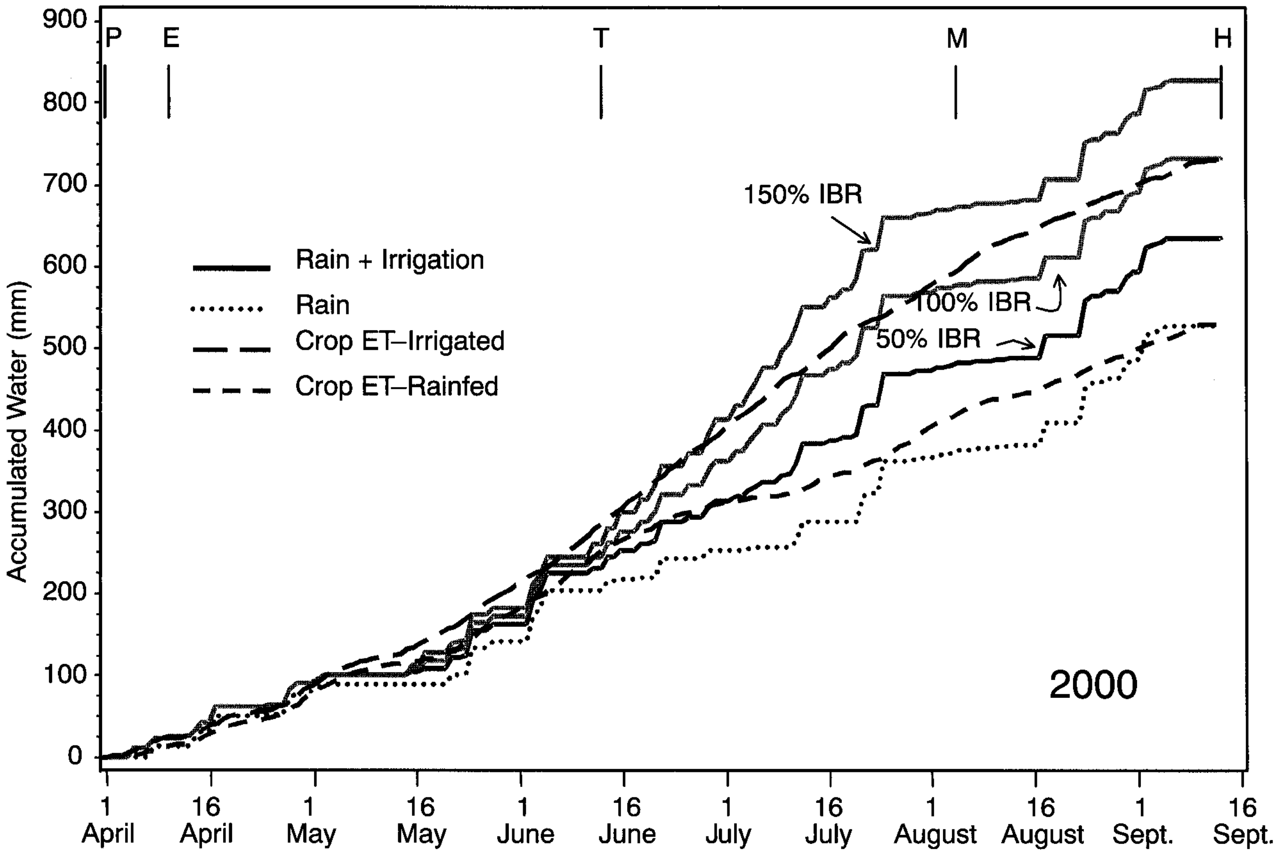


Figure 3. Cumulative rainfall, calculated rainfed and well–watered corn evapotranspiration, and rain plus irrigation for all irrigation treatments during the 2000 corn growing season. P, E, T, M, and H notations across the top indicate planting, emergence, tasseling, maturity, and harvest.

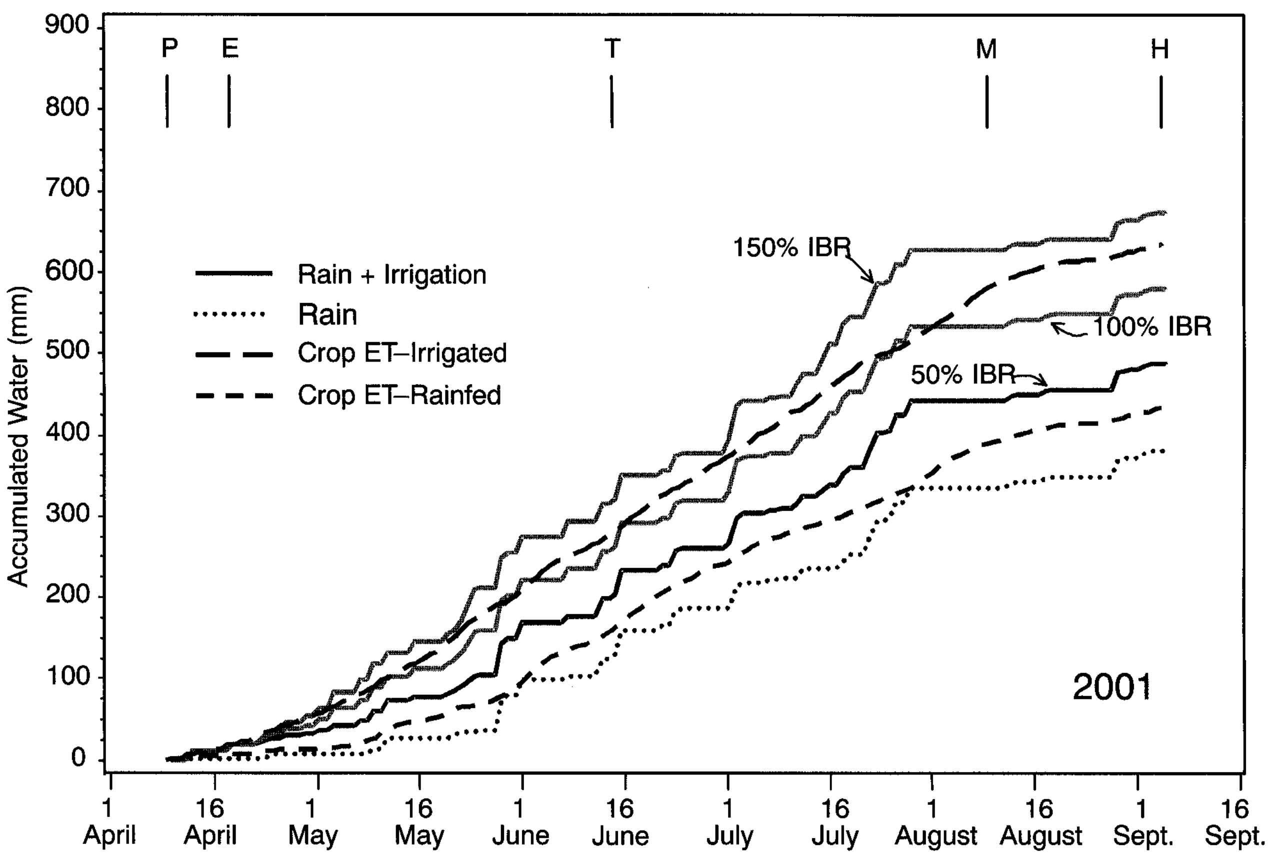


Figure 4. Cumulative rainfall, calculated rainfed and well–watered corn evapotranspiration, and rain plus irrigation for all irrigation treatments during the 2001 corn growing season. P, E, T, M, and H notations across the top indicate planting, emergence, tasseling, maturity, and harvest.

Table 3. Seasonal totals of rain, the three irrigation treatments, and calculated ET for grass reference (Eto), and both rainfed and well-watered corn (ETc) during 1999, 2000, and 2001. The small irrigation amount for the rainfed treatment was for germination, as all three spring planting periods were unusually dry. All values are in mm and are summed from planting to maturity, defined by GDU (growing degree units with limits of 10° C and 30° C). For comparison, climatic normals (1971–2000) indicate 410 mm during April through July.

		Rainfed	IBR			Rain	ETo	Etc	
			50%	100%	150%			Rainfed	Irrigated
1999	Irrigation	13	116	218	321	288	581	351	541
	Rain + Irrigation	301	404	506	609				
2000	Irrigation	11	107	203	299	371	618	410	583
	Rain + Irrigation	382	478	574	670				
2001	Irrigation	16	108	200	292	334	593	388	574
	Rain + Irrigation	350	442	534	626				

In all years, the cumulative evapotranspiration generally paralleled the 100% IBR treatment, despite the subsoil tensiometers indicating that irrigation was not penetrating to the lower root zone during much of the late season. Short periods existed during which the 100% IBR line was lower than the irrigated ET line near the end of the seasons. These generally coincided with the lower tensiometer readings, and they are consistent with historical observations in irrigated corn at this location. Despite the differences in rainfall in these three years (table 3), the irrigation amounts were surprisingly similar, with a total range of just 18 mm for the 100% IBR treatment.

The results of the analysis of variance for yield are shown in table 4. The dominant effect was, as expected, the irrigation variable, even in the wettest of the three years. This may not be representative of truly wet years in the area, as all three years received below–average rainfall. Orthogonal contrasts for both linear and quadratic forms of the irrigation effect were significant at the 1% level, and deviation from the quadratic form was not significant in any year. Since it was not possible to randomize the location of the soil treatment, the experimental design was constrained, and the test of significance for the soil main effect used the replication within soil as the error term. Even so, the variation among soil map units was significant in all years, the latter two at the 5% level and 1999 at the 1% level. However, the variation within soil map units was also significant at the 1% level, as seen by the replication within soil effect itself. In the first two years, the soil by irrigation interaction was significant at least at the 5% level. In 1999, there was a soil by N fertilizer interaction at the 5% level. In 2001, the N fertilizer amount effect was significant at the 1% level. That year, there was also a significant soil by irrigation by N fertilizer interaction.

These results are more easily visualized graphically. The soil–map–unit–mean corn response curves for 1999 and 2000 are shown in figures 5 and 6, respectively, averaged across N treatments. Given the significance of the N fertilizer effect in 2001, the low and high N curves are shown separately in figures 7 and 8, respectively. It is immediately obvious from the curves both that the means are different and that the ranked order of yields under rainfed and irrigated conditions is quite different for the soil map units. These results were obtained in all years, with the ranked order change most apparent in the first two. Especially in the first two years, the response to irrigation, as defined by highest irrigated yield minus the rainfed yield (IBR_0), was dramatically different across the soil map units. This is a graphic illustration of the significance of the soil by irrigation interaction. Values for this response are provided in table 5. Also shown in table 5 is a measure of the variation from the quadratic equations obtained for the RCB data. The r^2 for the equations ranged from 0.39 to 0.99 in 1999, with the wider variation in r^2 occurring in the soil map units with more blocks. Similar variation existed in 2000, with slightly lower r^2 values. Much lower goodness of fit was obtained in 2001, reflecting the much smaller range of yields obtained. It is easier to see this trend by following the predominant map unit, NkA, which had mean r^2 values of 0.73, 0.68, and 0.42 in the three years.

Year–to–year stability of the corn response curves would be desirable from the standpoint of being able to predict the effect of management, but in this 3–year period, two different types of curves were obtained. It is easier to see this result for a single soil, such as for NkA in figure 9. The 1999 and 2000 curves were similar in rising from a low value to a plateau, with a suggestion of a decline at the highest irrigation levels. On the other hand, the 2001 curve, for either N treatment, was almost symmetrical about the mean irrigation amount. It remains to be seen whether correcting for spatial runoff and redistribution suspected in 1999 and 2000 might bring these curves more into alignment.

Table 4. Analysis of variance results for the corn response to irrigation, N fertilizer, and soil map unit. Test for soil used replication within soil as the error term. Orthogonal contrasts for the (rain + irrigation) term are also given.

Source	DF	Mean Square Values[a]		
		1999	2000	2001
Error	268	1.3	2.5	1.3
Soil	11	13.2**	12.5*	4.4*
Rep (soil)	45	4.0**	5.9**	2.2**
UAN amount	1	1.0	6.8	14.7**
Rain + irrigation	3	153.9**	195.7**	8.6**
Linear contrast	1	277.0**	396.0**	12.3**
Quadratic contrast	1	16.9**	46.1**	11.2**
Deviation from quadratic contrast	1	1.2	0.1	0.1
Soil*UAN amount	9	3.0*	2.8	1.9
Soil*(rain+irrigation)	31	2.1*	4.4**	1.5
(Rain+irrigation)*UAN amount	3	1.7	3.5	0.9
Soil*(rain+irrigation)*UAN amount	22	1.2	1.5	2.4*

[a] * and ** indicate significance at the 5% and 1% level, respectively.

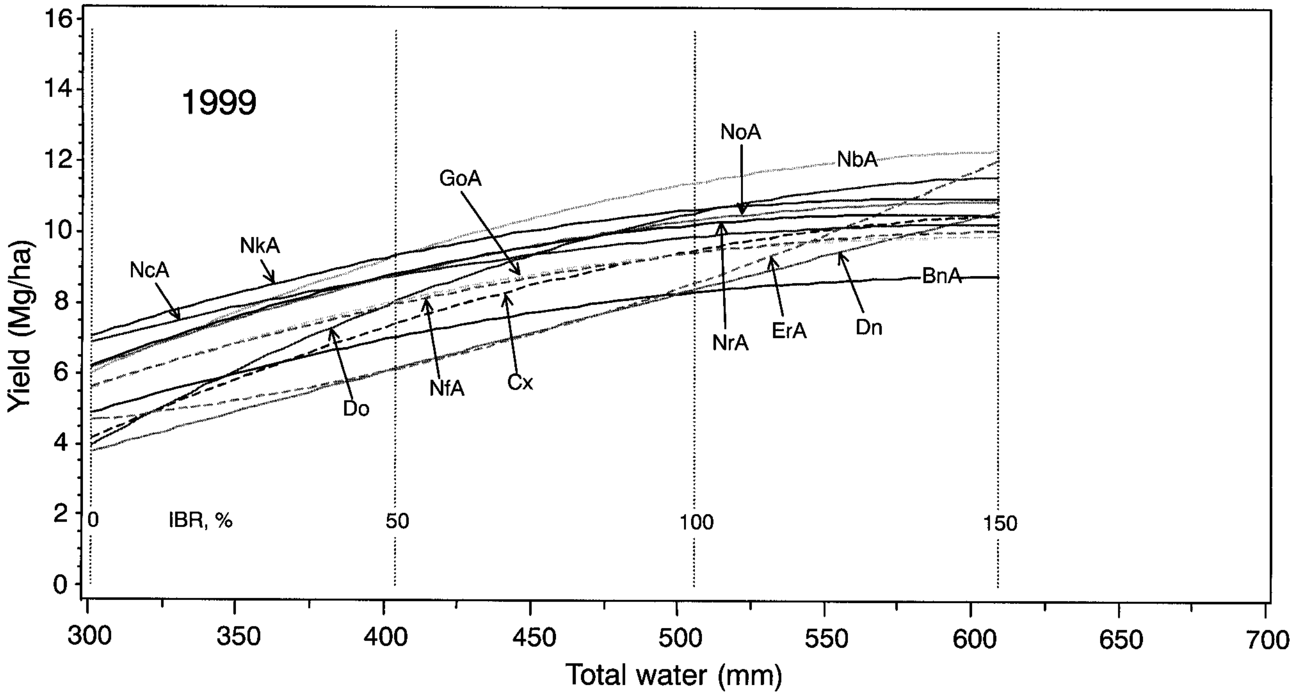


Figure 5. Map–unit–mean corn response curves to irrigation during 1999. Values are average of low–N and high–N treatments, which were not significantly different at the 5% level. Dashed curves for Cx, Do, ErA, and GoA were derived from RICB data only. IBR is irrigation base rate.

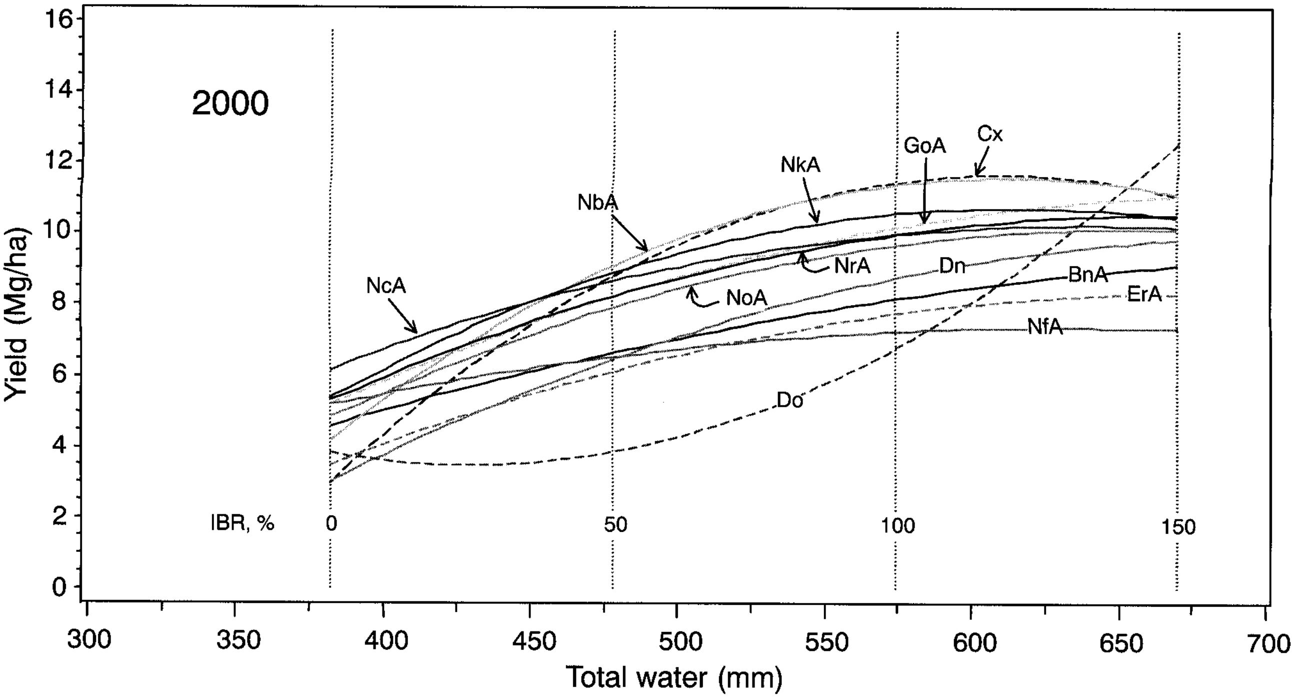


Figure 6. Map–unit–mean corn response curves to irrigation during 2000. Values are average of low–N and high–N treatments, which were not significantly different at the 5% level. Dashed curves for Cx, Do, ErA, and GoA were derived from RICB data only.

It is also necessary to consider the variation that occurs within a soil map unit. Recall that the replication within soil effect was significant at the 1% level in all years, indicating that the mean yields varied across blocks within a soil map unit. This can only be examined for a single map unit and year at a time. The NkA shown in figure 9 as a mean for all blocks is the most common map unit in this field. Therefore, for an example, the individual curves derived by fitting quadratic equations through all 8 plot–level values (including both N treatments) for all blocks are shown in figure 10. For this year, the r^2 for these curves ranged from 0.41 to 0.95, with a mean of 0.73 (table 5). The family of curves is reasonably parallel to the mean curve for 1999 (the heavy dashed line), but the curves shift up and down from block to block. Families of curves for other soils and for other years (not shown here) are similar.

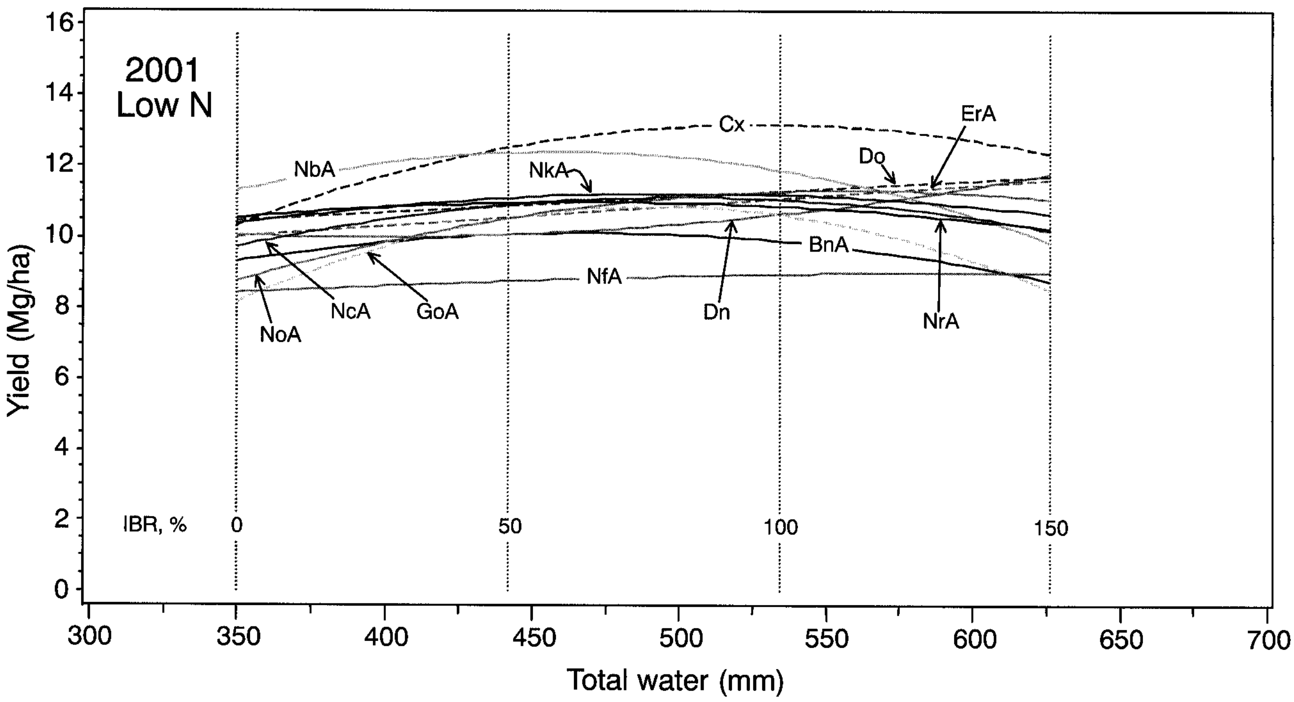


Figure 7. Map–unit–mean corn response curves to irrigation during 2001 for the 135–kg/ha N treatments. Dashed curves for Cx, Do, ErA, and GoA were derived from RICB data only.

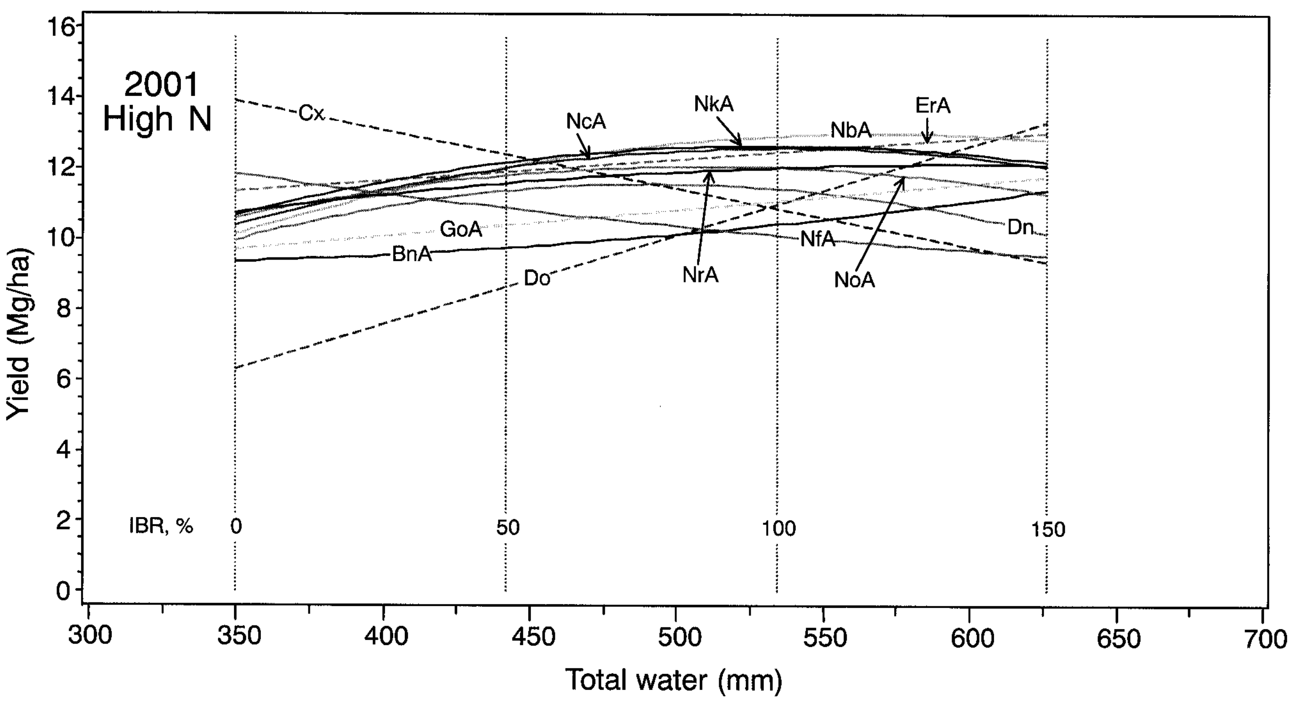


Figure 8. Map–unit–mean corn response curves to irrigation during 2001 for the 225–kg/ha N treatments. Dashed curves for Cx, Do, ErA, and GoA were derived from RICB data only.

The maximum yield, the irrigation value that obtained the maximum yield, and the maximum response to irrigation, all calculated from the quadratic equations fitted through the RCB data, are shown in table 5. While the formal economic analysis is beyond the scope of this article, the maximum yield and the irrigation value to obtain it are generally considered to approximate the optimum in the land–limited case (Martin et al., 1990). Variation in these values among soils and within soils under individual irrigation systems is critically important in their management. For 1999, the irrigation amount that would have produced the maximum yield varied from 187 to 321 mm, for a range of 134 mm. The 100% IBR irrigation amount was 218 mm, which means that the range of optimum irrigation amount was 61% of full irrigation. For 2000, the variation was from 175 to 299 mm, for a range of 124 mm, again 61% of the 100% IBR amount

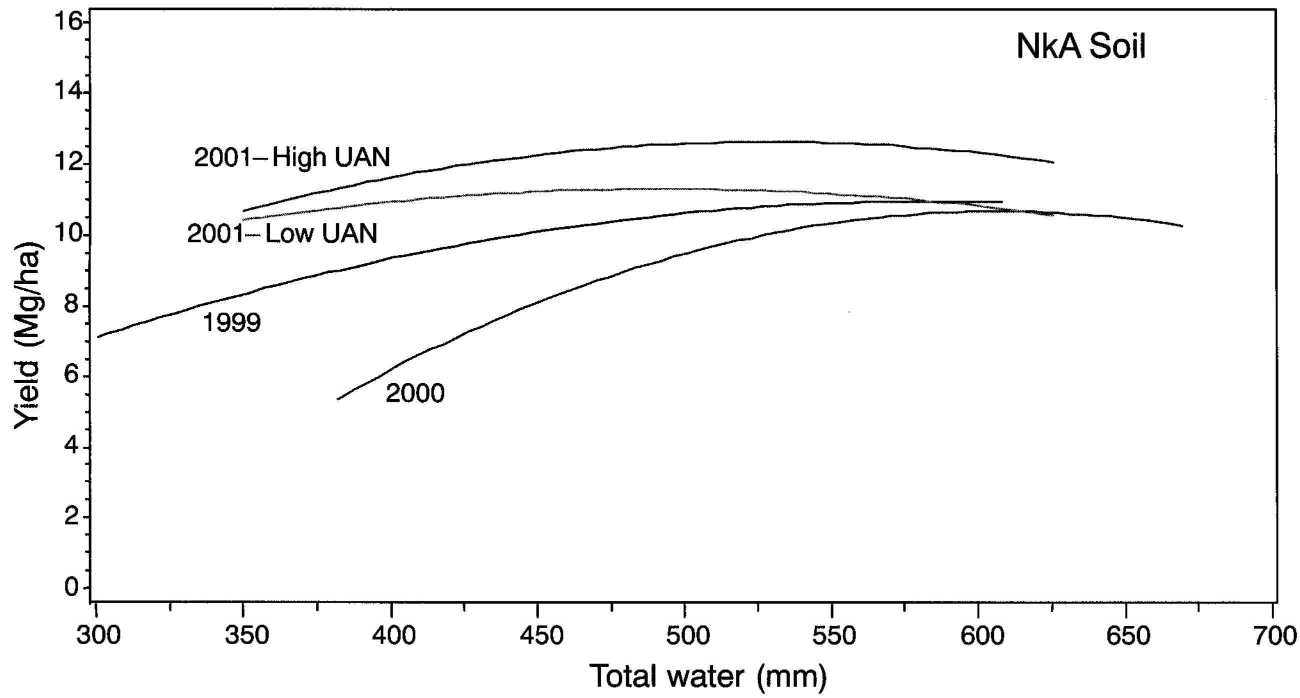


Figure 9. Mean corn response curves to irrigation for NkA soil map unit for all years.

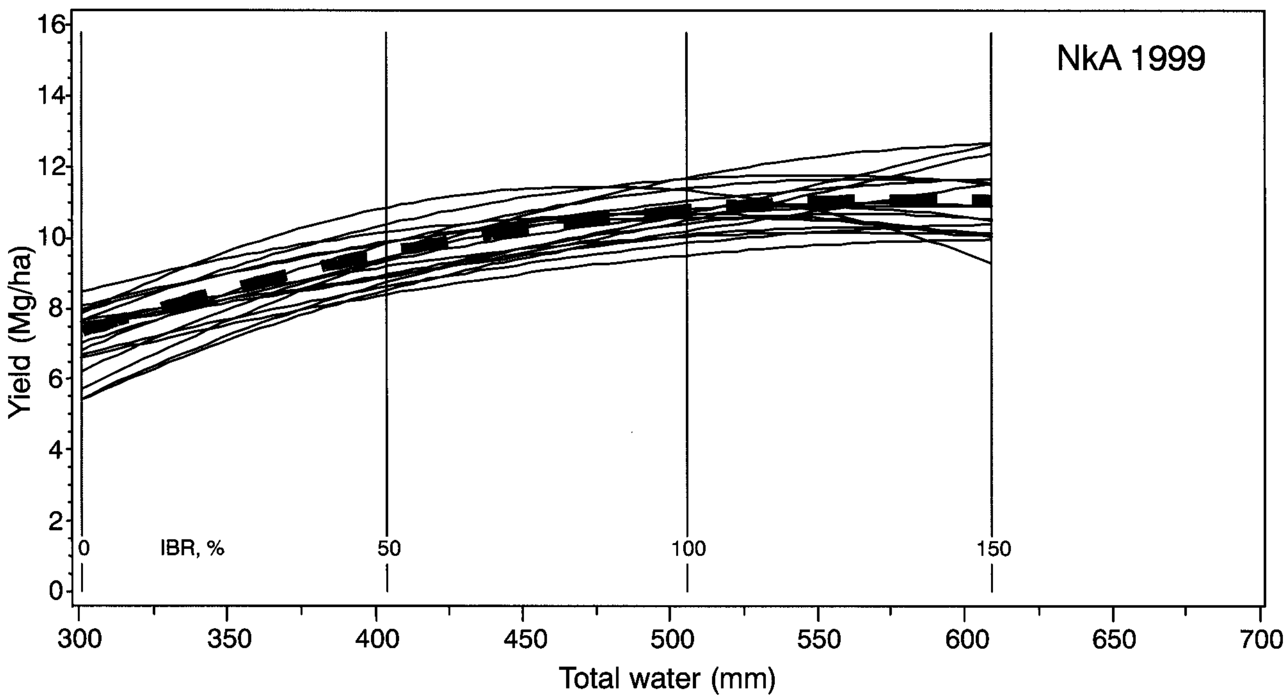


Figure 10. Individual block–level corn response curves to irrigation for the 1999 season.

of 203 mm. The variation in 2001 was from 53 to 292 mm, for a range of 239 mm, which was 120% of the 100% IBR amount of 200 mm. Since there was considerable variation in these maximum values, there would likely have been correspondingly large variation in the economic optimum values of irrigation for these soils during these years. This presents a significant challenge to managers seeking to achieve optimum management based on *a priori* information.

The results of this experiment have shown that significant variation in optimum irrigation amounts and response to irrigation can exist both among and within soil map units in southeastern Coastal Plain fields, and that this variation can occur within surprisingly short distances. This suggests that, during irrigation system design, the size of management zones may have to be reduced and the range of application rates may need to be increased. Further, the magnitude of the yield variation under irrigated conditions may be large enough that site–specific nutrient management plans may be justified. For regions with differential regulations for site–specific and whole–field nutrient management plans, or for

Table 5. Results of evaluating quadratic equations fitted for each RCB to calculate the maximum yield, the maximum response to irrigation for each map unit, and the irrigation value that produced the maximum yield.

	Map Unit	N[a]	Irrigation at Maximum Yield (mm)			Maximum Yield[b] (Mg/ha)			Response to Irrigation[b] (Mg/ha)			r^2 for Quadratic Equation		
			Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.	Min.	Mean	Max.
1999	BnA	1		321			6.5			3.1			0.75	
	Dn	2	321	321	321	10.5	10.6	10.7	6.1	7.2	8.2	0.85	0.87	0.89
	NbA	1		321			11.9			6.5			0.94	
	NcA	8	212	290	321	9.4	10.6	11.3	2.3	4.2	5.9	0.39	0.78	0.99
	NfA	1		276			10.0			4.2			0.62	
	NkA	18	187	281	321	10.0	11.2	12.7	2.5	4.4	7.5	0.41	0.73	0.95
	NoA	3	321	321	321	9.9	11.4	12.4	4.5	5.9	7.1	0.82	0.91	0.99
	NrA	5	200	281	321	10.5	10.9	11.4	3.0	5.0	6.6	0.40	0.78	0.92
2000	BnA	1		299			7.0			2.2			0.58	
	Dn	2	299	299	299	9.4	9.8	10.3	6.9	7.3	7.7	0.75	0.86	0.97
	NbA	1		256			11.7			8.0			0.96	
	NcA	8	213	256	299	8.5	10.3	11.3	1.6	4.6	7.5	0.19	0.64	0.86
	NfA	1		299			7.0			2.5			0.29	
	NkA	18	175	243	299	9.2	11.0	12.4	3.9	6.1	9.7	0.37	0.68	0.92
	NoA	3	247	282	299	9.8	10.3	10.8	4.1	6.2	8.1	0.71	0.84	0.91
	NrA	5	224	266	299	9.8	10.7	11.4	3.3	6.0	8.9	0.71	0.84	0.96
2001	BnA	1		174			9.3			1.9			0.16	
	Dn	2	167	230	292	10.9	11.3	11.7	1.1	1.4	1.8	0.05	0.24	0.43
	NbA	1		166			12.9			3.2			0.61	
	NcA	8	119	184	223	11.1	12.0	13.1	0.2	2.5	4.4	0.05	0.35	0.58
	NkA	15	53	183	292	11.6	12.4	13.5	0.1	2.2	5.2	0.09	0.42	0.83
	NoA	2	161	215	269	12.1	12.2	12.2	3.5	4.0	4.4	0.58	0.63	0.68
	NrA	4	171	186	201	11.2	11.6	11.8	0.5	1.3	2.3	0.03	0.23	0.55

[a] Number of randomized complete blocks (RCB). Number of points for each quadratic equation is 8.
[b] Maximum yields computed from quadratic equation in Mg/ha less rainfed yield (A_O) in Mg/ha.

regions or periods with water resource allocation restrictions, regulatory and record–keeping requirements may need to be considered in system design as well. Additionally, these results suggest that there would probably be an interaction between irrigation management and economic thresholds or profitability. Irrigation management under conditions of limited water resource or regulated allocation restrictions would be particularly impacted.

Summary and Conclusion

The results of this experiment showed conclusively that significant differences existed in the response of corn to irrigation, both across soil map units and within soil map units. While this result is somewhat expected from a theoretical standpoint, the differences were quite large. Two qualitative factors make the observed differences even more striking. The first is the scale of the soil map, which, at 1:1200, is approximately an order of magnitude finer than the usual for a county soil survey. Thus, one would have expected map unit differences at this scale perhaps to be more subtle. This suggests that soil map unit (soil classification) may be of limited utility in site–specific farm decisions. The second factor is the relatively short distance over which these differences were obtained. The center pivot is only 140 m long, covering about 6 ha. It is known that variation increases with distance, leading one to consider what might be found under a 400–m pivot covering 8 times the area.

Ultimately, determining whether variation within soil map unit is so large as to require further study at scales even finer than those considered here will require geostatistical or other spatial analyses. For now, it is clear that differences between map units exist at magnitudes likely to be important in irrigation system design and management. This finding should alert irrigation system managers and designers about the need to consider more strongly the effects of unexpectedly large spatial variation in crop response. It also should open the way for further research, for a complete economic analysis, and analysis of variation on a spatial rather than map–unit scale.

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